Evolution of the Accelerator Alignment Methods at DESY over the past thirty years

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1. INTRODUCTION

The DESY accelerator system today consists of the synchrotrons DESY III (Protons) and DESY II (Electrons or positrons) as preaccelerators, the storage ring PETRA II and the main storage rings HERA (Fig. 1). Additionally the storage ring DORIS III is used as synchrotron radiation source.

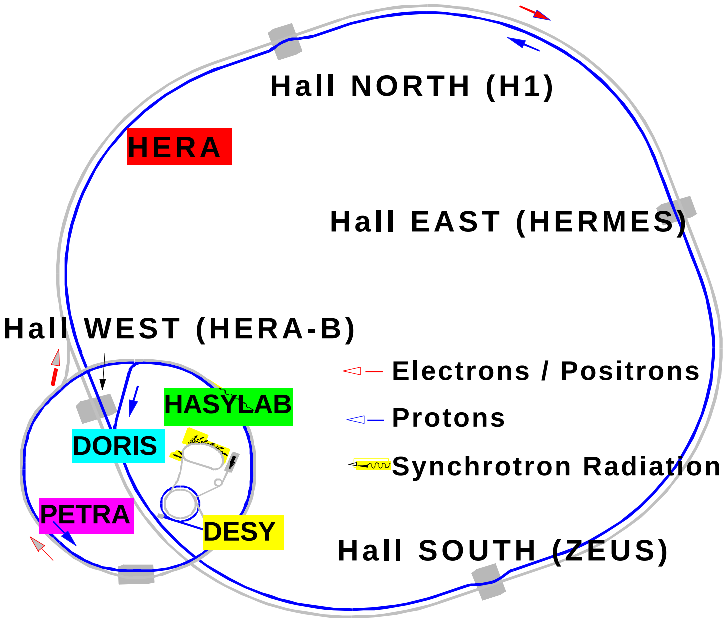


Figure 1: DESY accelerators

The various accelerators were developed and modernized one after another over the past 35 years. The synchrotron DESY started operation in 1964 with 40 combined function magnets of 20 tons each. The storage ring DORIS was ready for commissioning in 1974, this time based on separated function magnets. Such magnets were also used in the following machines, the e^-, e^+ storage ring PETRA which went into operation 1978 and the e^- ring of HERA, ready for acceleration in 1988. The proton ring HERA with superconducting magnets in the arcs followed in 1991, so that collision experiments have been possible since 1992. Between 1984 and 1988 a new e^- - synchrotron was installed in the DESY tunnel, the old DESY machine was rebuilt to be used as proton synchrotron and the necessary linear accelerator for protons was mounted in one of the former experimental halls at DESY. PETRA finished its physics program in 1986 and was then prepared for its function as preaccelerator for HERA.

2. THE ELEKTRON - SYNCHROTRON DESY

For the alignment of the DESY magnets an absolute accuracy of ±0.1 mm transverse to the beam line was required. To fulfill this challenge an expensive magnet support system had to be constructed and, additionally, care had to be taken to reach the demanded accuracy by geodetical methods.

2.1 The magnet support

The precise machined magnets were placed on a concrete ring (Fig. 2) on top of pendulum supports. This construction should shift the whole ring rather than cause a deformation by radial forces. Cooling pipes on the surface of the concrete ring and additional insulation should prevent thermal influence.

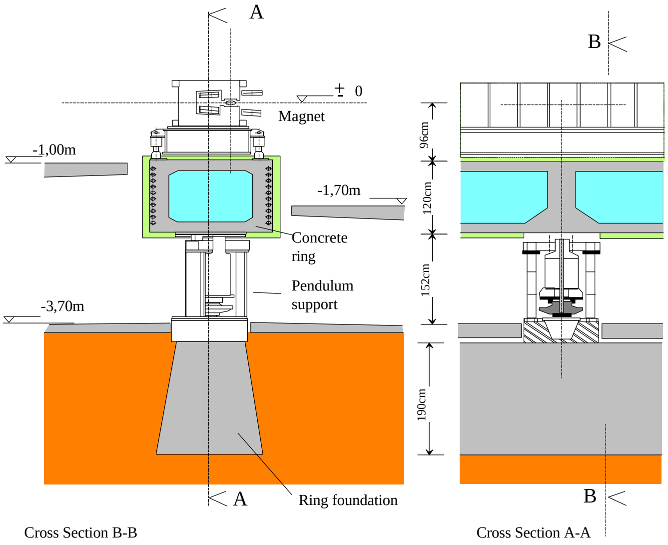


Figure 2: Foundation of the synchrotron DESY

These demands at first were only partially fulfilled. The ring proved to be not stiff enough to keep its form. After installation of bellows for the RF connections to the cavities and loosening of the cables from the power supplies this problem was solved. Another problem arose because the cooling of the concrete ring at the beginning was run via two water circuits. The water temperature could not be controlled with the necessary accuracy at that time, so the temperature differences of the two circuits often caused an unacceptable roll of the magnets. These influences were eliminated when the same circuit was used for cooling. One problem was still left: the diameter of the concrete ring was strongly dependent on the water temperature of the ring cooling in spite of good airconditioning in the tunnel. Only better temperature stabilization could prevent this effect. In the first years of operation, we always had to fight this problem. Today, with the old DESY magnets still resting on the same concrete ring, but accelerating protons and having another layout (DESY III), the electronic regulation of the water temperature guarantees a stable diameter of the magnet ring .

2.2 Alignment of the synchrotron

To reach the required absolute accuracy for the magnet alignment, we chose a reference system similar to one already used at CERN. Eight concrete pillars, deeply founded, were erected in the corners of a regular octagon, one pillar was positioned in the center. Each side of the octagon was devided in three parts by two additional pillars (Fig. 3). All these pillars carry centering marks for mounting Kern - theodolites and targets as well as microscopes for reading the graduation of invar tapes.

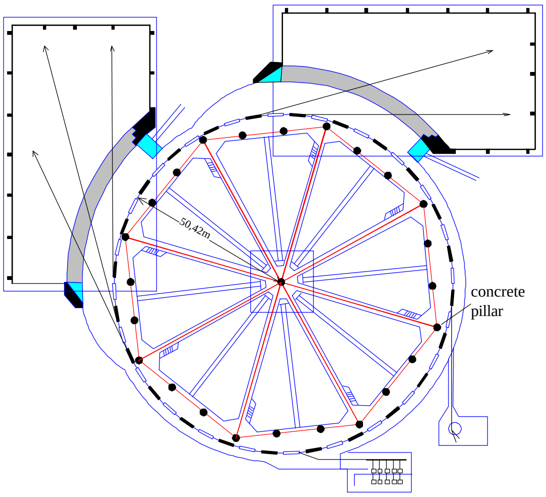


Figure 3: DESY Layout

The form and scale of the synchrotron was mainly defined by this pillar octagon. The distances between the pillars were measured using calibrated invar tapes, the only way at that time to reach high distance measurement accuracies. Fig. 4 shows the measuring device: the reading microscope centered on the Kern - mark, the low friction pulley and the 98 N weight for stretching the tape. By reading the graduation at both ends of the tape simultaneously the distances between the pillars could be determined with standard deviations better ±0.03 mm. The standard deviations of the coordinates did not exceed ±0.05 mm once the measurements were adjusted to the nominal position of the pillars.

Figure 4: Invar tape measuring device

The coordinate transfer from the octagon to the accelerator magnets could be performed easily. The magnets were positioned on the concrete ring such that one Kern - centering mark on top of every 7th magnet was arranged within the line from the center to the neighbouring octangular pillar (Fig. 5). The coordinates of these marks were determined by polar measurements from the pillars HVP. The angles α were measured with precision theodolites Kern DKM 3 (Fig. 6) and special targets (Fig. 7), which allowed standard deviations of better than ±0.4 mgrades for one set of angular measurements over distances from 1.7 m up to 50 m. The distances *s* were derived from measurements with a special ruler, read once more with the microscopes. The length of this ruler was calibrated with respect to the octagon by angular measurements on the pillars.

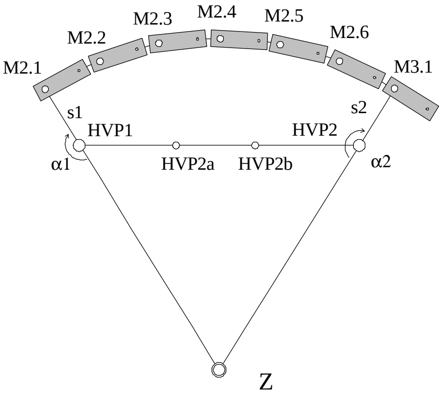


Figure 5: Connection reference- and magnet system DESY

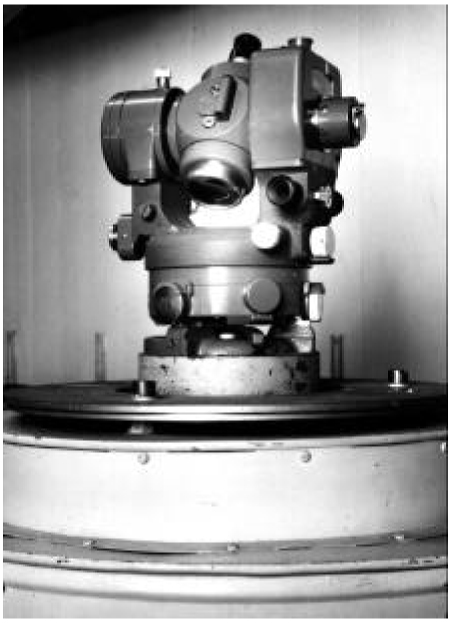
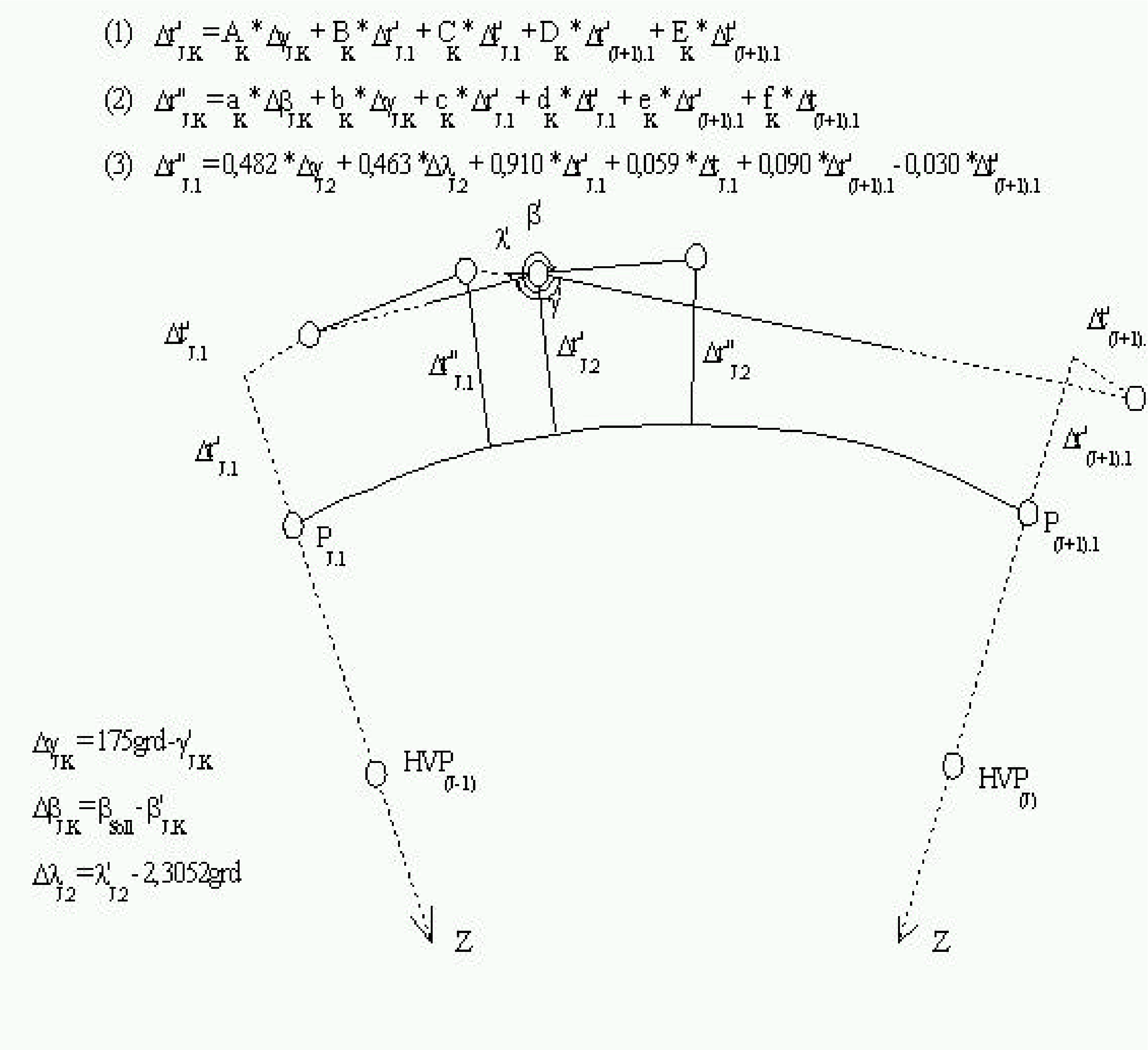


Figure 6: Kern theodolite on pillar

Figure 7: Target for horizontal angle measurements

All magnets in between one octant now could be referenced to the two neighbouring centering marks $M_{I.1}$ and $M_{(I+1).1}$ by measuring the periphery angles γ' (Fig. 8). Deviations from the nominal value 175 grades allow the evaluation of the corresponding radial deviations $\Delta r'$

from the nominal position, dependent on the known values $\Delta r'_{I.1}$, $\Delta t'_{I.1}$, $\Delta r'_{(I+1).1}$ and $\Delta t'_{(I+1).1}$, with a very high accuracy. From many independent measurements of the whole magnet ring we could evaluate a standard deviation of a single measurement for Δr' of ±0.07mm. Deviations in beam direction are here without any influence if they are corrected within 1mm. This was reached easily by normal tape measurements which gave standard deviations of about ±0.3mm, if a stretching gauge was used.



$$(1)\quad \Delta r'_{IK} = A_K * \Delta\gamma_{IK} + B_K * \Delta r'_{I.1} + C_K * \Delta t'_{I.1} + D_K * \Delta r'_{(I+1).1} + E_K * \Delta t'_{(I+1).1}$$

$$(2)\quad \Delta r''_{IK} = a_K * \Delta\beta_{IK} + b_K * \Delta\gamma_{IK} + c_K * \Delta r'_{I.1} + d_K * \Delta t'_{I.1} + e_K * \Delta r'_{(I+1).1} + f_K * \Delta t_{(I+1).1}$$

$$(3)\quad \Delta r''_{I.1} = 0{,}482 * \Delta\gamma_{I2} + 0{,}463 * \Delta\lambda_{I2} + 0{,}910 * \Delta r'_{I.1} + 0{,}059 * \Delta t_{I.1} + 0{,}090 * \Delta r'_{(I+1).1} - 0{,}030 * \Delta t'_{(I+1).1}$$

$$\Delta\gamma_{IK} = 175\text{grd} - \gamma'_{IK}$$

$$\Delta\beta_{IK} = \beta_{Soll} - \beta'_{IK}$$

$$\Delta\lambda_{I2} = \lambda'_{I2} - 2{,}3052\text{grd}$$

Figure 8: Determination of the radial displacements at DESY

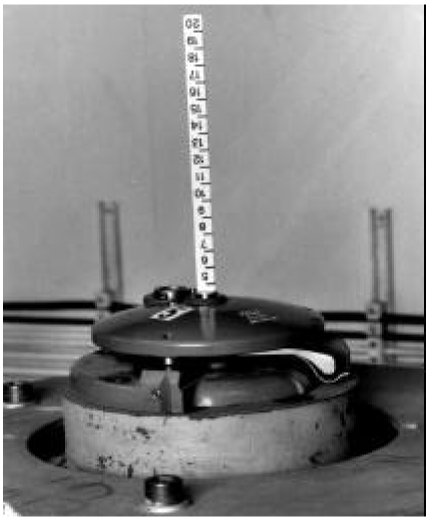


Figure 9: Leveling ruler

The height measurements for the synchrotron were much easier. With precision leveling instruments Wild N3 the height differences between the pillars of the octagon were determined and the heights evaluated from a least square adjustment. For the measurement leveling rulers were used which were resting on spheres inside the socket of the Kern centering plate (Fig. 9). These rulers could also be used on top of the synchrotron magnets while measuring two leveling lines for each octant (Fig. 10). The heights of the magnets were evaluated with a standard deviation of ±0.08 mm with respect to the nominal horizontal plane. These values also define the accuracy of the determined pitch of the magnets, while their roll was measured with bubble inclinometers to some 0.01 mrad.

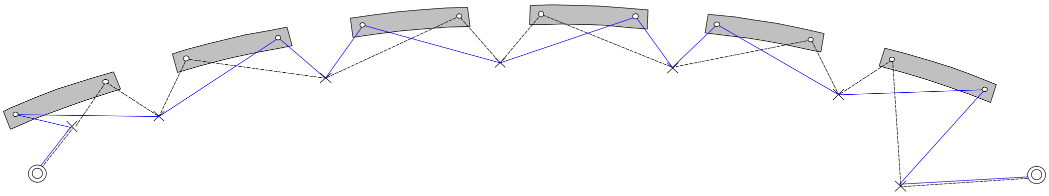


Figure 10: Observation scheme for leveling at DESY

2.3 Alignment of the beam lines to the DESY experiments

As long as DESY was used as beam source for high energy physics, transport systems had to be installed between the DESY-tunnel and the experimental halls. Such systems contained dipoles and quadrupoles which had to be aligned within some tenths of a millimeter to their nominal position. To avoid the constraints given at that time by the limited possibilities of length measurements we equipped those magnets with special reference plates (Fig. 11). The surface was precisely machined for roll-measurements with the bubble inclinometer. A conical

Figure 11: Reference plate for beam line magnets

target as well as a leveling ruler could be inserted into the socket. On top of the reference plates auxiliary posts could be mounted which carried cantilevers with precision scales perpendicular to the magnet axis. They could be zeroed with respect to the socket of the plate using an adjusting level centered by spherical fittings. When the bottom plate was horizontal and the cantilever adjusted and fixed, the target on top had an offset from the magnet axis as shown by the reading of the scale (Fig. 12).

After adjustment of height and roll the alignment transverse to the beam could be accomplished according to the sketch in Figure 13. The beam line next to the synchrotron was aligned directly from a suitable reference mark of a machine magnet. Because its position was known from the accelerator survey, the offset *p* from the nominal beam line of the transport system and the set out angle of the parallel line could be evaluated and used for the alignment, if all the targets on the cantilevers were set to the value *p*. Distance measurements in this case were only necessary for positioning of the first dipole within 2 mm along the beam.

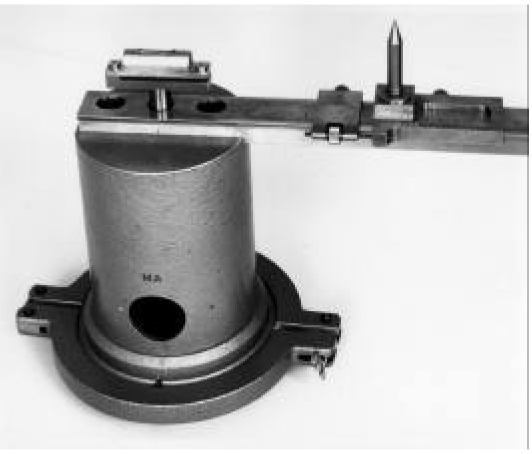


Figure 12: Eccentric target for beam line magnets

The alignment procedure for the rest of the beam traverse was similar. The theodolite was mounted on the center plate of the respective dipoles, the offsets *E* from the hinge point of the beam traverse and *e* from the beam line according to the bending angle had to be determined and taken into account for the readings of the targets on top of the magnets (Fig. 14).

This method allowed the installation of the DESY transport systems within the required relative accuracy. It was also used for the later beam lines to the storage rings DORIS and PETRA.

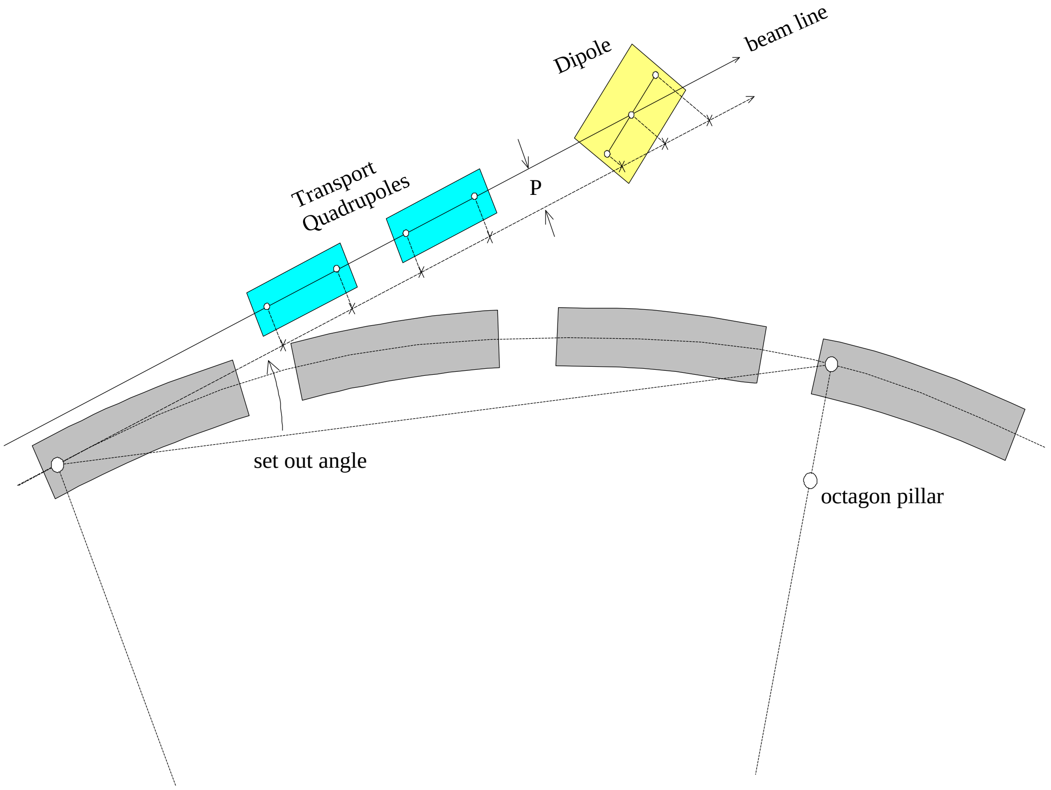


Figure 13: Alignment scheme for beam line magnets near the synchrotron

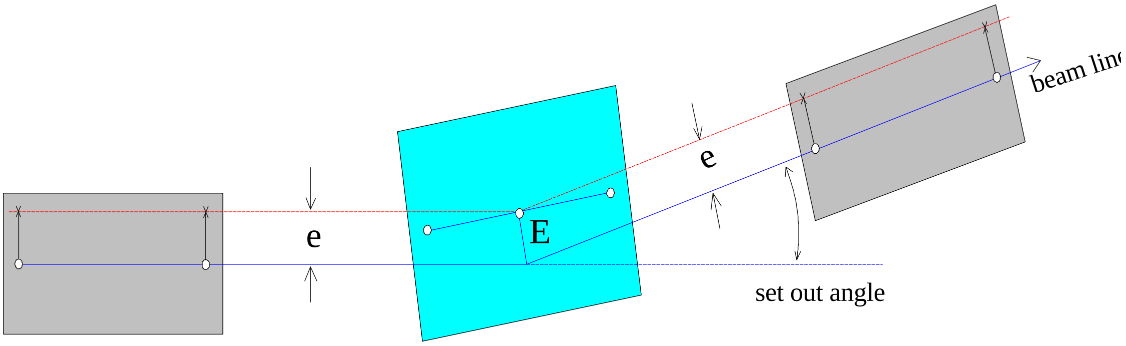


Figure 14: Alignment scheme for beam line magnets along the traverse

3. THE STORAGE RING DORIS

During operation of the synchrotron it became obvious that the absolute alignment of the magnets is not nearly as important as the relative accuracy of positioning within a certain range which is defined by the β - oscillation of the accelerated particles. At DESY the 6th to 8th harmonics had to be minimized for the machine to operate properly.

Similar conditions existed for the operation of the second ring accelerator on the site, the storage ring DORIS. Here a relative alignment of ±0.2 mm with respect to the smoothed curve of the remaining offsets was defined sufficient for this machine.

To guarantee the stability of the alignment special foundations were chosen. The magnets in the arcs are resting on heavy concrete blocks clearly separated from the tunnel building. In the long straight sections the magnets are directly mounted on the tunnel floor which at that area has been strongly reinforced.

For the alignment of the magnets once more a reference system of concrete pillars similar to those at DESY was chosen (Fig. 15). The position on the circumference was defined by the symmetries of the magnet distribution. In the arcs of the four quadrants, with three dipole doublets each, the pillars were arranged at the center of the connecting straight sections such that four Kern reference marks on top of the dipoles were on axis with the pillars. On the other hand, the dipole marks adjacent to the straight section were set in line with the corresponding beam axis. So the position of every quadrant was defined by four pillars. The long straight sections between the arcs were devided in equal parts by two additional pillars near the interaction region. The corresponding beam axes coincide with the connecting lines of the reference marks on the dipoles at the end of the arcs [1].

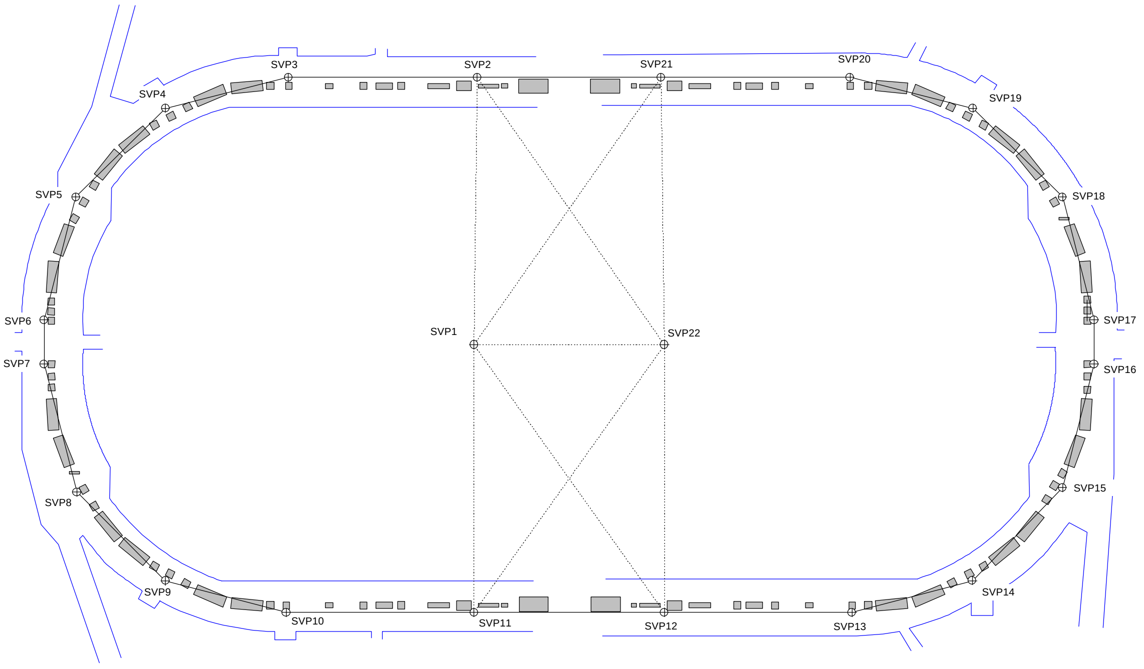


Figure 15: Layout of DORIS

The conditions for the measurements at that time, 1974, were still the same as in 1964. So the distances between the 20 pillars on the circumference had still to be determined with invar tapes. Because of the newly defined alignment requirements, we were restricted this time to measuring a closed traverse with connections of the two long straight sections via two additional pillars in the DORIS hall. This was necessary because the detectors at the interaction points interrupted the connection of the neighbouring pillars on the circumference, once they were mounted.

Figure 16: Straight section DORIS with 1m-scale bar on interaction quadrupole

For the alignment of the magnets the accuracy of the angular measurements was again crucial. The radial position of the dipole marks was derived from theodolite measurements on these marks to the neighbouring pillars. Simultaneously, the adjacent quadrupoles were measured. The radial position of these quadrupoles could be determined with an approximate distance from the theodolite, while the distance of the dipole mark from the pillar had to be measured with a special scale bar to about ±0.2 mm. The interaction quadrupoles near the experiments could be directly aligned from the neighbouring pillars, using additional Kern marks at the side nearly on axis with the pillars, and were controlled by polar measurements to the reference marks on top (Fig. 16).

Height and roll measurements for DORIS were performed similar to DESY. Machined plates on top of the magnets gave the reference.

4. THE STORAGE RING PETRA

The construction of the storage ring PETRA brought a new scale into the alignment considerations at DESY. With a circumference of about 2.3 km it was remarkably larger than the existing accelerators. 692 separated function magnets, quadrupoles and dipoles, had to be positioned. The alignment requirements were similar to those of DORIS: the remaining offsets after smoothing the quadrupole displacements from nominal position should not exceed ±0.2 mm. The fit should not contain harmonics of the 23th to 25th order and guarantee an accuracy of the circumference of the machine of minimum 3.10^{-6}.

Classic pillar systems as reference for the alignment were not possible any more. Instead a surface net had to be installed to provide the scale of the machine (Fig. 17). This net was the first to be measured with the new electronic distance measuring instrument Kern ME 3000 (Mekometer), which gave standard deviations of ±0.5 mm for the measured distances derived from the least square adjustments (Fig. 18).

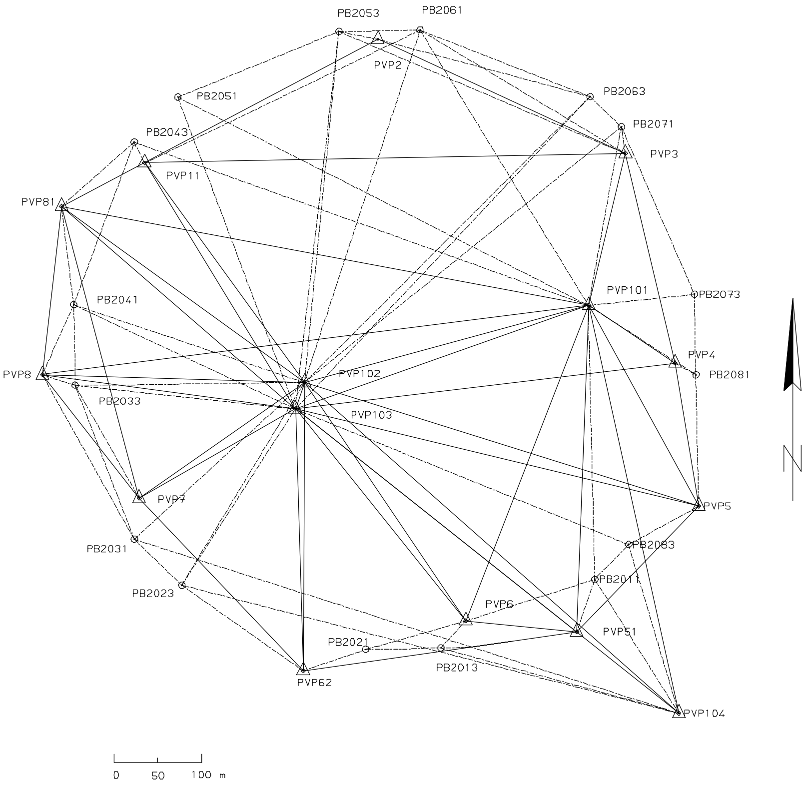


Figure 17: PETRA surface net

Figure 18: ME3000 on top of a building

The coordinate transfer from the surface net into the PETRA tunnel was performed via measurements to vertical steel pipes from the tunnel ceiling to the surface. These pipes are located at the ends of the PETRA arcs and can be equipped with movable endpipes. Their heads (Fig. 19) can be aligned approximately vertical above reference sockets in the floor of the accelerator, using a Kern precision plumbing instrument, before the distance measurements with the Mekometer. Remaining offsets can be taken into account by measuring zenith angles from the tunnel points to that on top of the pipes. By this method the radial position of the reference sockets in the tunnel floor could be determined with a standard deviation of about ±0.6 mm with respect to the PETRA center.

Figure 19: Survey pipe above the PETRA-tunnel

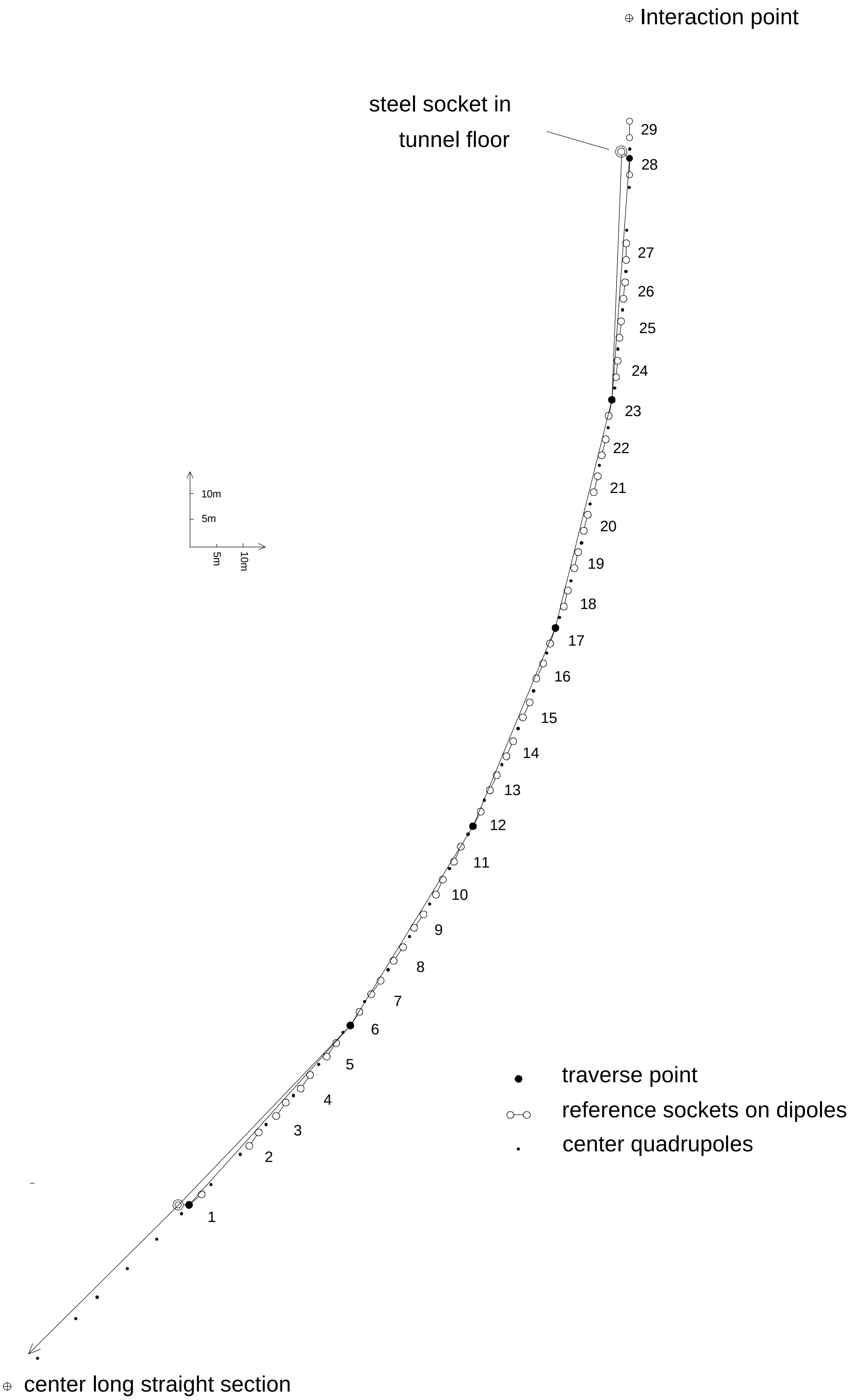


Figure 20: Magnet traverse for one octant (PETRA)

This accuracy proved to be sufficient for the alignment of the magnet string between two floor sockets of every octant. Six equally distributed Kern centering marks on dipoles defined a magnet traverse (Fig. 20) which could be measured with Kern DKM3 theodolites and the Mekometer and was connected to the reference sockets by a least square fit. Magnets in between the traverse points were determined by angular measurements from the intermediate dipoles (Fig. 21), pointing at the neighbouring traverse points and the adjacent dipoles and quadrupoles. For the distances between the dipoles and to the quadrupoles average values were introduced into the calculations which had been determined immediately after the first installation of the magnets with the 1 m scale bar or the CERN distinvar respectively [2].

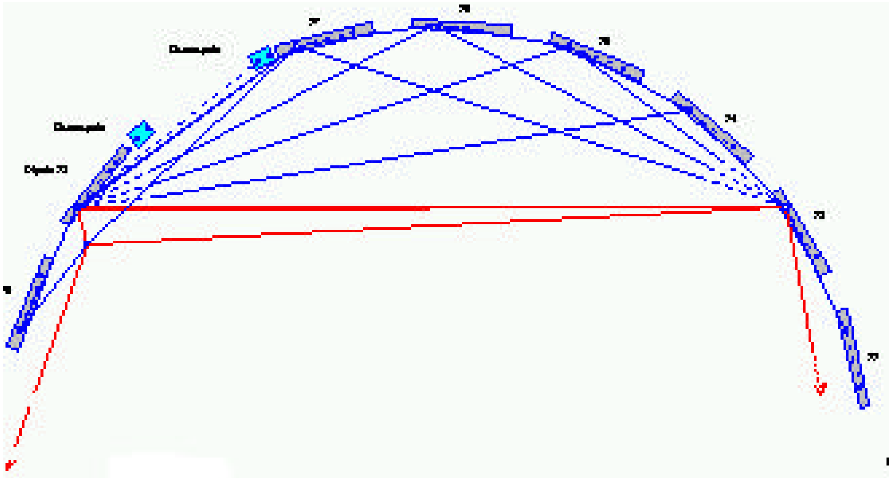


Figure 21:Angular measurements between the traverse points

Because no azimuthal alignment was foreseen for the PETRA magnets, only the evaluated radial displacements from the nominal position were important. These values usually showed systematic deformations which were caused by thermal effects in the tunnel and, to a certain degree, by the constraints between the surface net and the tunnel traverse. These deformations could be eliminated by least square fits of the values with respect to polynomials up to the third order. The remaining offsets then were taken into account for the alignment of the magnets and led to the required radial accuracy.

For the height measurements spherical bolts were inserted in the tunnel floor next to every second quadrupole (about 14 m apart). The height differences between these bolts can be determined by precision leveling (Ni1, N3, Ni002) over the circumference of the whole accelerator. Systematic effects on these measurements have to be evaluated and eliminated. This is possible by a comparison of the determined heights with those from an earlier measurement and a least square fit of the differences based on a Fourier analysis up to the 8th order. The such determined height of the bolts in the floor until today gives the reference for the vertical alignment of the magnets with the leveling rods directly resting on the magnet surface.

5. THE HERA SYSTEM

The alignment of the HERA accelerators gave another challenge. Once more a surface net provides the reference with vertical pipes up to the surface in one corner of every hall to transfer the coordinates into the tunnel (Fig. 22).

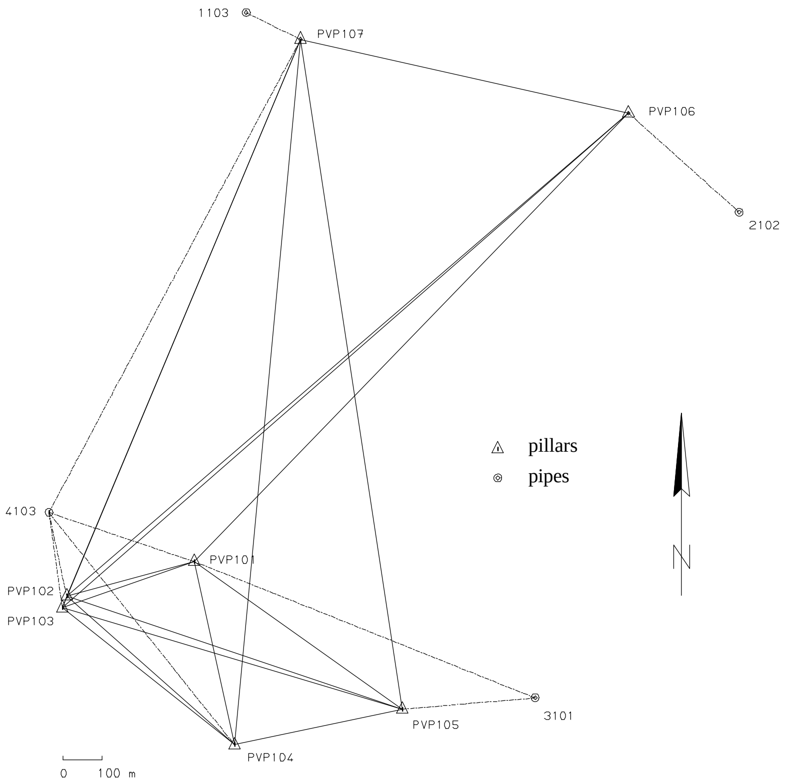


Figure 22: HERA - surface net

An underground closed traverse with overlapping angular - and distance measurements containing the points below the vertical pipes can be determined using E2 theodolites and the Leica ME 5000 within ±3 mm with respect to the HERA center (Fig. 23). Learning from the experiences at PETRA, the HERA traverse can pass the detectors in the experimental halls via the traverse points in the corners of the halls. Thus the relative accuracy of the adjacent straight sections is guaranteed, which was not the case at PETRA. The accuracy of two neighbouring octants there was given only by that of the surface net.

The underground traverse points are defined by so called auxiliary pillars mounted on steel centering plates on the concrete floor with Kern plates on top (Fig. 24).

For height measurements once more spherical reference bolts were inserted in the concrete floor such, that precision leveling in the tunnel is possible and the height of the auxiliary pillars can be determined.

For the alignment of the magnets we had to take into account that the machine planes are not horizontal anymore, but have an inclination of 10 mrad. While separate alignment steps were and are possible for all our other accelerators for height and radial position we now had to install a three dimensional alignment method for the 6335 m long HERA rings [3], [4], [6].

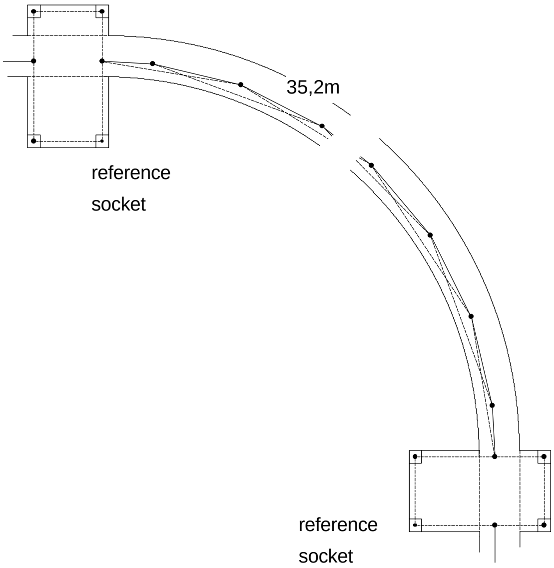


Figure 23: Underground reference traverse HERA

Figure 24: Centering plate and auxiliary pillar

That means that horizontal and vertical positions as well as rotations have to be corrected simultaneously.

We chose conical sockets which are centering Taylor Hobson spheres with targets for angular- or reflectors for distance measurements (Fig. 25). These sockets are mounted on platforms attached to the side of the magnets such, that the centers of two Taylor Hobson targets together with the measured roll of the platforms define the position of the magnet axis.

A special support for the instruments was developed which allows centering on top of the conical HERA socket via a spherical base with the same diameter as that of the Taylor Hobson spheres. Thus horizontal and vertical angular measurements with electronic theodolites can be carried out as well as distance measurements with the ME 5000, even on inclined survey platforms, referenced directly to the center of the Taylor Hobson sphere underneath (Fig. 26).

Figure 25: Taylor Hobson sphere on HERA-socket

Figure 26: Survey platform with centering support for theodolite

For the prealignment of the magnets, one socket could directly be determined by angular measurements from the magnet to the neighbouring auxiliary pillars of the tunnel traverse (Fig. 27). All data were immediately transferred to a computer. After additional distance measurements to a scale bar on top of the next auxiliary pillar the computer could evaluate the position and height of the stand point socket and the nominal angular readings for pointing at the neighbouring magnet sockets. The theodolite then only had to be set on these readings so that the telescope was pointing at the corresponding targets and the magnets had to be moved as far as necessary to cover the targets with the cross hair of the theodolite. To facilitate this step we at that time used normal CCD-cameras which were mounted behind the ocular (Fig. 28). The images of the target and the crosshair were transferred to a screen such, that a technician could move the magnet horizontally and vertically for himself until the crosshair covered the target center (Fig. 29). Simultaneously he had to control the readings of a Husky computer which showed the actual and nominal roll of the two platforms of the magnet measured by Schaeviz inclinometers. By this method the technician in situ could decide if the alignment was good enough to be finished.

Figure 27: Prealignment with respect to the tunnel traverse

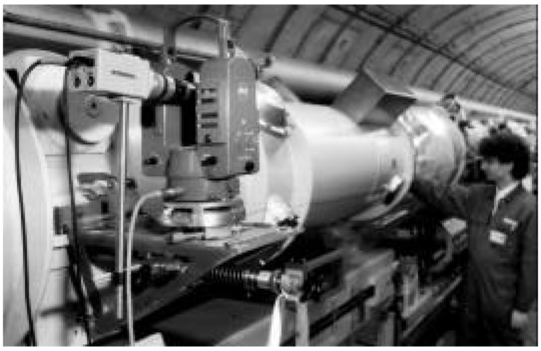


Figure 28: CCD - camera behind the theodolite

Figure 29: Image of the target on TV

The final alignment of the HERA machines once more is based on angular measurements. Assuming that all magnets are prealigned radially with an absolute accuracy of better than 5 mm with respect to the HERA center by referencing to the tunnel traverse, the relative accuracy of adjacent magnets can be obtained by a roundabout measurement on the circumference of the accelerators. As stand points for the instruments, symmetrically located magnet sockets are chosen. For the superconducting magnets in the arcs of the HERA proton machine one socket of every quadrupole is used (Fig. 30). All these stand points define a traverse which can be determined by angular and distance measurements. Redundancy is provided by pointing to either two preceding and two following traverse sockets. Magnets in between two stand points are pointed at from both instrument positions so that every socket is measured at least twice.

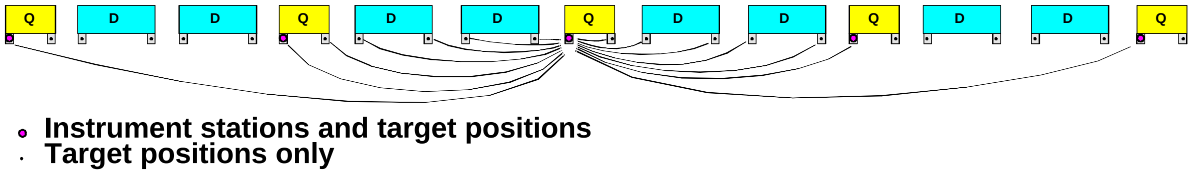


Figure 30: Observation scheme HERA-p

These measurements can be performed without connections to the tunnel traverse. To avoid excessive errors due to systematic influences on the measurement, we usually include the traverse points below the vertical plumbing pipes into the magnet traverse as fixed points for the least square adjustment of the observation data. Thus we can achieve radial displacements from the nominal position as shown in Fig. 31. The remaining deformations are smoothed by a cubic spline function taking into account the β - functions of the machine.

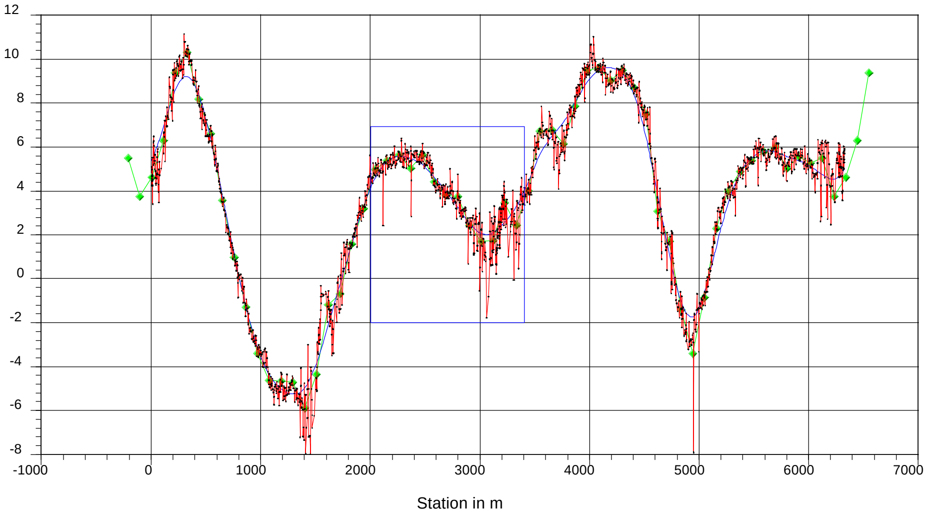


Figure 31: Radial displacements in [mm]

In contrast to the height measurements for the older accelerators on the DESY site the HERA magnets are not determined by a precision leveling. Since the prealignment with respect to the tunnel traverse already gives a pretty good vertical position of the magnets, the precision measurements are carried out by measuring the vertical angles to the targets simultaneously with the horizontal angles, one pointing giving both values to the computer. At the beginning of the HERA measurements, there were restrictions for the height results because only the distances between the traverse points on the magnets were determined with the ME 5000 from both sides. So only the traverse could be measured with enough redundancy. The magnet sockets in between the traverse points at that time, however, were only taken into account with their nominal distances from the instruments, thus generating differences between the two height determinations of the same socket according to the position accuracy in beam direction.

Since 1994 we use the total station Leica TC 2002 for the HERA measurements. The angle measuring accuracy is the same as that of the Kern E2, the distance measuring accuracy is better than 0.2 mm and good enough for the traverse measurements on the circumference. With this instrument we need ~ 30 % less time for the measurement of one machine (e^-, p), as only one survey team is necessary now. The distances to all intermediate magnet sockets are now measured in addition. This eliminates the influence of azimuthal misalignments on the determination of their vertical position via vertical angular measurements.

Under these conditions, a three dimensional least square adjustment of the observation data (horizontal and vertical directions, distances) is possible, which gives the displacements from the nominal position of the magnet sockets. After smoothing of the results by cubic spline functions the actual radial and vertical correction values are available for the alignment. Which, of course, has to be carried out also considering the roll of the survey platforms.

6. CONCLUSION

The alignment procedure developed for the HERA machines has proved a success. In the meantime, we are using it also for our other accelerators by measuring traverses mainly on top of the quadrupole magnets along the machine circumference [5], [7].

To sum it up one can state that the fundamental procedures for accelerator alignment at DESY have not been changed over the past 30 years. We still are measuring angles and distances, but the instrumentation has been improved (Fig. 32).

Figure 32: DESY instrumentation

We started in 1964 with theodolites Kern DKM 3 and invar tapes for the position measurements. From 1975 on the Kern Mekometer ME 3000 facilitated the measurements of the reference systems. Only in 1984 the first electronic theodolite Kern E 2 was available. It improved the accuracy of a measured direction to better than 0.2 mgrades and gave the possibility to transfer the data immediately to a connected hand held computer. The ME 5000 came just in time for the HERA - tunnel measurements in 1986. Because of its high accuracy it completely replaced the invar tape measurements and could directly be integrated into the magnet measurements. The last improvement for the accelerator survey at DESY was achieved by the introduction of the total station TC 2002 which gave the opportunity to measure angles and distances with the same instrument. Together with the advanced computer technology we now are able to carry out our accelerator surveys with the required accuracy, a minimum of man power and in an acceptable time.

7. REFERENCES

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